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Low Frequency Atmospheric Noise Studies and Long Wave Technology Interfaces

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The results of the work done under contract DNA 001-93-C-0146 are discussed. This work included changes and improvement to the long wave noise propagation code LNP, development of a new ground conductivity model for use in LNP and as a separate code. In addition, under this contract we demonstrated that LNP could be used in a system to forecast noise levels in a manner similar to weather forecasts. The techniques developed to do this are discussed.

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SUMMARY

This report summaries the long wave propagation and noise techniques developed under contract DNA-001-93-C-0146. This work can be divided into the following topics:

1. The development of techniques to forecast global lightning occurrence from currently available weather data for use in dynamic long-wave noise calculations.

2. Improvements and extensions to the long-wave noise prediction code LNP.

3. Improvements and extensions to the ground conductivity model.

4. Validation of the results of LNP.

Summaries of the work done on each of these topics are given in the following sections.

CONVERSION TABLE

Conversion factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ————————————→ BY ————————————→ TO GET
TO GET ←———————————— BY ←———————————— DIVIDE

angstrom	1.000 000 X E -10	meters (m)
atmosphere (normal)	1.013 25 X E +2	kilo pascal (kPa)
bar	1.000 000 X E +2	kilo pascal (kPa)
barn	1.000 000 X E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 X E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 X E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 X E +1	*giga becquerel (GBq)
degree (angle)	1.745 329 X E -2	radian (rad)
degree Fahrenheit	$t_k = (t°f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 X E -19	joule (J)
erg	1.000 000 X E -7	joule (J)
erg/second	1.000 000 X E -7	watt (W)
foot	3.048 000 X E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 X E -3	meter^3 (m^3)
inch	2.540 000 X E -2	meter (m)
jerk	1.000 000 X E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 X E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 X E +3	kilo pascal (kPa)
ktap	1.000 000 X E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 X E -6	meter (m)
mil	2.540 000 X E -5	meter (m)
mile (international)	1.609 344 X E +3	meter (m)
ounce	2.834 952 X E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 X E -1	newton-meter (N·m)
pound-force/inch	1.751 268 X E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 X E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 X E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 X E -2	kilogram-meter^2 (kg·m^2)
pound-mass/foot^3	1.601 846 X E +1	kilogram/meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 X E -2	**Gray (Gy)
roentgen	2.579 760 X E -4	coulomb/kilogram (C/kg)
shake	1.000 000 X E -8	second (s)
slug	1.459 390 X E +1	kilogram (kg)
torr (mm Hg, 0° C)	1.333 22 X E -1	kilo pascal (kPa)

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (GY) is the SI unit of absorbed radiation.

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SECTION 1

INTRODUCTION

The study of the performance of long wave strategic communication systems under average conditions is a well understood task, and a number of computational tools exist to aid the analyst. Since such communication systems are atmospheric noise limited, knowledge of the ambient noise level as a function of time of year and time of day is very important in any system study. For this reason the Defense Special Weapons Agency and the Office of Naval Research sponsored the development of the long wave noise prediction code, LNP. LNP has been under development since 1989, and its first version was released in 1991. Under contract DNA-001-93-C-0146 Version 4 of the code was developed and released. Most of the tasks performed under this contract were centered on improvement to LNP, either direct improvements and extensions to the code itself, the method of validating the code, or improvements to one of the underlying model that LNP uses. These tasks are summarized in Sections 3, 4 and 5. The task described in Section 2, was an attempt to determine if LNP could be extended into the new area of forecasting noise in the same way as weather is forecasted.

All the versions of LNP, including Version 4, produce predictions of the average expected noise for a given frequency, location, month, and time of day. However, at long wavelengths, atmospheric radio noise is produced by lightning and the both the location and intensity of lightning flashes varies from day to day. Thus one would expect that the day to day variation of noise level any given location could be very large. Indeed, during summer afternoons, the noise level can be 7 dB or more above the long term average noise level on 10 % of the days. Thus, such operational questions as how a predicted thunderstorm system will affect a particular transmitter's coverage cannot be directly answered using LNP. These types of questions require a system that can both determine the actual worldwide noise levels at the present time and one that can forecast noise levels for the foreseeable future. We call such a system a dynamic noise forecasting system.

An operational dynamic long wave noise forecasting system will require the ability to dynamically forecast lightning, both its location and its intensity. Since the noise power from lightning can propagate for long distances, to produce predictions for even small geographic areas requires knowledge of lightning over a large area. Thus for actuate noise forecasts we will have to forecast lightning nearly everywhere on the earth. This

means we will need to determine the number of lightning flashes per second per km^2, (called the flash rate density), as a function of geographic location world wide. Section 2 of this report discusses some of the techniques we have found for doing this.

SECTION 2
LIGHTNING FORECASTING METHODS

The lightning forecasting study had two parts. First determine if we could determine the lightning flash rate density from current weather maps accurately enough to predict noise, and then develop procedures to forecast this parameter for some days into the future. Although there are several ground based lightning detection systems[1] in certain areas of the world, none cover a wide enough area to be useful in determining the current lightning distribution by themselves. Any lightning detection system would not be able to forecast the occurrence of future lightning in any case. Thus this study looked for empirical relationships between commonly available weather information and lightning flash rates.

Weather services, such as the National Weather Service, provide three basic types of information: current weather, forecasted weather, and forecasted parameters. By current weather we mean those weather observations published in real or near real time. These include the location of severe storms, Doppler radar summaries, ground temperature and wind velocity, etc. For our purposes the most important of these real time products are satellite cloud images and the parameters that can be derived from them, in particular cloud top height. Forecasted weather means the above parameters protected forward in time for up to four to five days. Forecasted parameters are those weather service products that are computed from direct observations and which are used in making weather forecasts. We found two of these, called the lifted index and convectively available potential energy (CAPE) – both measures of atmospheric instability – that are correlated with flash rate.

The forecasting methods developed be grouped into three areas depending on the kinds of data used:

1. Those based on current weather observations. These observations include direct flash rate observations from ground or satellite systems where available. Otherwise cloud top heights from either Doppler radar or satellite images can be used to compute flash rates. By following the flash rate patterns from these observations over a period of time, we can project these patterns forward in time. These forecasted flash rates can

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[1] No satellite systems provided continuous flash rate data when this study began. However, NASA has recently made data from the Optical Transient Detector on the Microlab-1 satellite available.

be used up to eighteen to twenty-four hours in advance before other techniques give better results.

2. Those based on computed weather parameters. We have found that lifted index and CAPE when combined with either the projected storm patterns discussed above or other severe weather forecasts can be use to predict flash rates with sufficient accuracy for our purposes. Although CAPE appears to be a slightly better flash rate predictor, it does not seem to be predicted on a regular basis, where as lifted index is normally predicted up to 48 hours in advance.

3. Those based on forecasted weather maps. We have also developed a method to estimate flash rates from forecasted weather maps that can be used in the absence of other forecasts. This technique uses the geographic area covered by the forecasted thunderstorms to infer flash rates. The method is not as accurate as other methods, but can be used to predict the general trend in noise levels.

The lightning forecasting methods are described in detail in Warber and Sinclair [1996]. This report reviews atmospheric and lightning physics, derives the empirical relationships discussed above, then presents the forecasting methods based on these relationships. Finally we show representative examples of the predictions, discuss the requirements for an operational system, and suggest a plan to deploy one. Results from this report were presented at the Ionospheric Effects Symposium, held May 7-9, 1996 in Alexandria Virginia. The IES paper was selected for a special issue of Radio Science. It will be published as Warber and Prasad [1997].

The ability to dynamically predict noise will have its greatest effect at the edges of a transmitter's coverage region. If the receiver is close enough to the transmitter it should be able to receive signals even during a strong storm, and if it is too far away it will not receive on the quietest days. Figure 2-1, taken from Warber and Sinclair [1996] is an example of the change in coverage from the 24 kHz, 1200 kW transmitter at Cutler Maine on a day with no storms near the operational region as well as the change caused by a large storm system. For this example we considered coverage to the European operational area. The solid line is the nominal coverage limit, the dashed line is the limit on a day when a large thunderstorm system was over central and eastern Europe, and the dotted line is the limit on a day when the closest storm was in the south eastern Africa area.

The present study was limited to a single season of a single year. More work is needed to expand the prediction techniques to other seasons. Expanding the study to use more
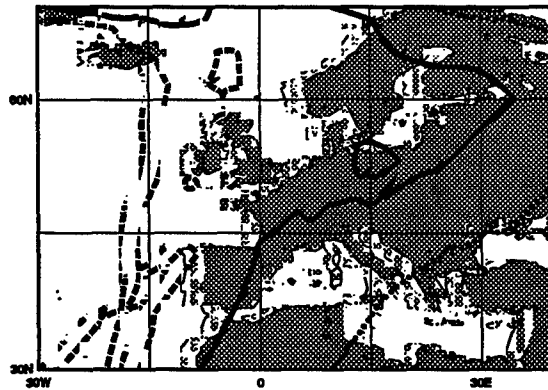
4

Figure 2-1. Coverage from Cutler transmitter for average conditions (solid line), noisy conditions (dashed line), and quiet conditions (dotted line) during July 1400 UT.

data from a number of years should improve the techniques and increase our confidence in them. In the present study data was chosen to exclude periods of significant severe weather such as hurricanes. Further study is needed into the lightning flash rates caused by these weather conditions.

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SECTION 3
IMPROVEMENTS TO LNP

LNP, the longwave noise prediction code, has been under development for several years. Version 4 of LNP was released under this contract. This version uses a new ground conductivity model (described in Shearer and Davis [1993], and Warber [1997]) which accounts for changes in conductivity due to changes in ground temperature. The frequency range over which LNP produces valid atmospheric noise predictions has been extended down to 5 Hz. In addition LNP now incorporates an ultra low frequency (ULF) geomagnetic noise model developed by Bloom *et al* [1995] for frequencies below 1 Hz. Under this contract the users manual [Warber, 1996] was revised to bring it up to date with the above changes and to make it easier to use.

SECTION 4

GROUND CONDUCTIVITY MODEL

In the mid 1960s the Westinghouse Electric Corporation and the Naval Research
Laboratory, developed a set of effective ground conductivity maps for use at very low
frequencies. The conductivities given on those maps are estimates based on the
geologies known at that time and are subject to substantial uncertainty as well as seasonal
variability. In 1993 Pacific-Sierra Research introduced an new ground conductivity
model for Canada that used the latest knowledge of the geology of that region, as well as
a model of the effects of temperature on the conductivity of water saturated rocks.
Under the current contract we extended the earlier work to all regions of the Northern
Hemisphere where permafrost occurs. In addition the original computer code was
extensively revised, both to make it work seamlessly with LNP, and to make it easier to
interface with other long wave propagation codes. The report, [Warber 1997], discusses
the physical basis of the model, and is also a user's manual for the computer code, called
GRNDCOND.

SECTION 5

VALIDATION OF LNP

The noise predictions made by LNP are validated using an automated procedure developed under an earlier contract. Central to this procedure is the computer code VALID. VALID is used to maintain a database of experimental noise measurements that were made over a number of years during three different atmospheric noise projects. The longest and largest of these projects was the one conducted by the National Bureau of Standards, as it was then called. This started in 1957 and continued for ten years. Data for this project were taken at 15 sites distributed worldwide. In LNP's frequency range the NBS experimenters measured noise levels at 13kHz, and 51 kHz, but not all sites took data at these frequencies for the entire experimental period. The second project was conducted over a similar time period by Russian experimenters. Their data sites were located within the Soviet Union. These sites took at several different VLF frequencies that varied with the site. The third project was that conducted by Stanford University from 1986 to 1990. This project took data at seven sites, although not all the sites took good data for the entire period. This project took data in a number of frequency bands from 10 Hz to 32 kHz. For validation of LNP only the data below 300 Hz and above 8 kHz were used.

The VALID code examines the experimental noise data, generates LNP command sets that match the conditions for which the data was taken. Once LNP has been run for all these commands sets VALID compares LNP's predictions to the corresponding experimental data point, and can display these comparisons in a number of ways. This procedure allows us to isolate problems with LNP's noise algorithms and to make the proper adjustments. The procedure is described in detail in Buckner et al. [1994].

Originally the valid experimental database contained NBS data from only 1957 to 1959. Under this contract this was expanded to the full length of the NBS project. Also the entire data set was examined and data that was questionable was eliminated from the data set. In some cases where the original reports indicated problems with the equipment, only individual data points where removed, but in other cases all the data from certain sites was eliminated because of problems, chiefly man-made noise, at the site. Man-made noise was a problem during all the projects.

The resulting experimental data set makes up, we believe, the best available long-wave

noise data. This set was used to validate the latest release of LNP – Version 4. The procedure did uncover some small problems during development of this version and allowed us to correct them before the code was release.

One draw back with the VALID procedure is that it can be very time consuming to run. Depending on the type and number of computers used it can take several days to complete the entire procedure. On the 100 MHz Pentium used during the current contract, for example, it took 4 days – running the computer only during non-work hours to generate the predictions needed. For this reason VALID has an option that allows the operator to look at only part of the database, in order to concentrate on a particular problem area. Thus allows the needed LNP runs can be done in a shorter period of time. However, before the release of any version of LNP, a full VALID run is now always made.

SECTION 6

CONCLUSIONS

During this contract LNP was improved and extended. It can now predict long wave noise down to 10 Hz, and it can automatically call the Geomagnetic Noise model to produce noise predictions below this frequency. The conductivity model used by LNP has been made dependent ground temperature so that LNP can better model high latitude noise as a function of the time of year.

During this contract, we have shown that it is possible to predict lightning occurrence up to four to five days into the future. Warber and Sinclair [1996] give recommendations as to how the techniques we developed can be used to extend LNP to dynamically forecast atmospheric noise. More work is needed in this area to extend the techniques to other seasons however.

One drawback to the use of forecasted weather as the basis for the lightning predictions is that the lightning forecasts can be no better than the weather forecasts. However, lightning forecasts do not have to be as precise as normal weather forecasts because the ultimate use of the lightning forecasts is as input to the noise model. Noise power propagates over long distances so that at any one location the average noise level is a result of a number of storm systems. For example, calculations have shown that errors in location of storm systems on the order of 500 km have barely discernable effects on the total average worldwide noise levels. The noise model is more sensitive to errors in flash rate intensity, but even these kinds of errors tend to average out if the total worldwide flash rate is approximately correct.

One development that we did not explore during this contract is the new worldwide flash rate data available from NASA's Optical Transient Detector, OTD. A major criticism of LNP is that its underlying lightning occurrence database contains only two years of data. The OTD data could be used first to check LNP's lightning database and then, if the OTD program continues, to replace it. The OTD data would also be important in the proposed dynamic noise forecasting system.

SECTION 7

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